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INITIATION AND PROPAGATION OF SMALL CORNER CRACKS

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ABSTRACT

The behaviour of small corner cracks, inclined or perpendicular to loading direction, is presented. There are two aspects to this investigation: initiation of small cracks and monitoring their subsequent growth. An initial pre-cracking procedure under cyclic compression is adopted to minimize the residual damage at the tip of the growing and self-arresting crack under cyclic compression. A final fatigue specimen, cut from the larger pre-cracked specimen, has two corner flaws. The opening load of corner flaw is monitored using a novel strain gauge approach. The behaviour of small corner cracks is described in terms of growth rate relative to the size of the crack and its shape.

INTRODUCTION

Experimental observations indicate that initiated fatigue cracks first grow in a shear mode, which is termed Stage I after Forsyth [1]. After growing through a few surface grains at about 45 degrees, the actual macroscopic crack plane rotates to become normal to the far-field maximum principal stress. This is termed Stage II or Mode I in fracture mechanics terminology. The transition in crack direction from Stage I to II is generally of a crystallographic nature, and is associated with specific favourable slip systems in a polycrystalline solid. It has been also observed that during Stage I/II transition period the actual rate of propagation is highly variable. This erratic growth is usually ascribed to the grain boundary blocking mechanisms of the metallic microstructure [2-6].

In general, small cracks exhibit faster growth rate than that predicted based on the long-crack methodology, and they even grow below the threshold for long cracks [7-9]. These apparent "anomalies" of small crack behaviour may be influenced by a number of factors such as:

(i) the lack of appreciable crack closure for small cracks due to the limited length of crack wake [eg. 9-11];

(ii) the actual crack aspect ratio, a/c, i.e. the ratio of crack depth a to the half surface crack length c being small, and

(iii) the crack plane orientation.

The effect of the latter two factors have not been investigated in a systematic manner. This is probably because most experimental studies are limited to small semi-elliptic surface cracks. In this type of investigation the crack depth behaviour is estimated from the surface crack measurement. Unfortunately, in such approaches, the crack aspect ratio, a/c, as well as the crack plane orientation, cannot be directly observed.

This paper presents a methodology, recently developed by the authors [12-14], which is used in investigating the behaviour of small corner cracks in a carbon steel. By employing this technique, the principal variables of corner cracks such as crack depth, crack aspect ratio as well as its plane of orientation can be measured. A pre-cracking procedure under cyclic compression [10] was adopted to minimize the residual damage left at the tip of a corner flaw. The opening load of the corner flaw is monitored using a novel strain gauge approach [14]. The behaviour of small corner cracks, inclined and perpendicular to loading direction, is presented in terms of growth rate relative to the size of the crack and its shape.

SPECIMENS AND EXPERIMENTAL PROCEDURES

The material investigated is the ASTM A-516 Gr. 70 carbon steel having tensile strength 540 MPa and 0.2% proof stress of 325 MPa. The mechanical properties of this ferritic/perlitic steel and the chemical composition are described in detail elsewhere [15].

Specimens

Final specimens with small corner flaws are manufactured in two stages as shown schematically in Fig. 1. First, a side-grooved compact-type (CT) specimen is pre-cracked in cyclic compression. The crack, which initiates from the notch, is permitted to grow until it self-arrests. A fatigue tension (FT) sample is subsequently cut from this pre-cracked specimen so as to include just the tip of the crack. This results in two small corner cracks because the fatigue crack front under cyclic compression has a concave shape. This shape can be influenced by the notch geometry as described in Ref. [16].

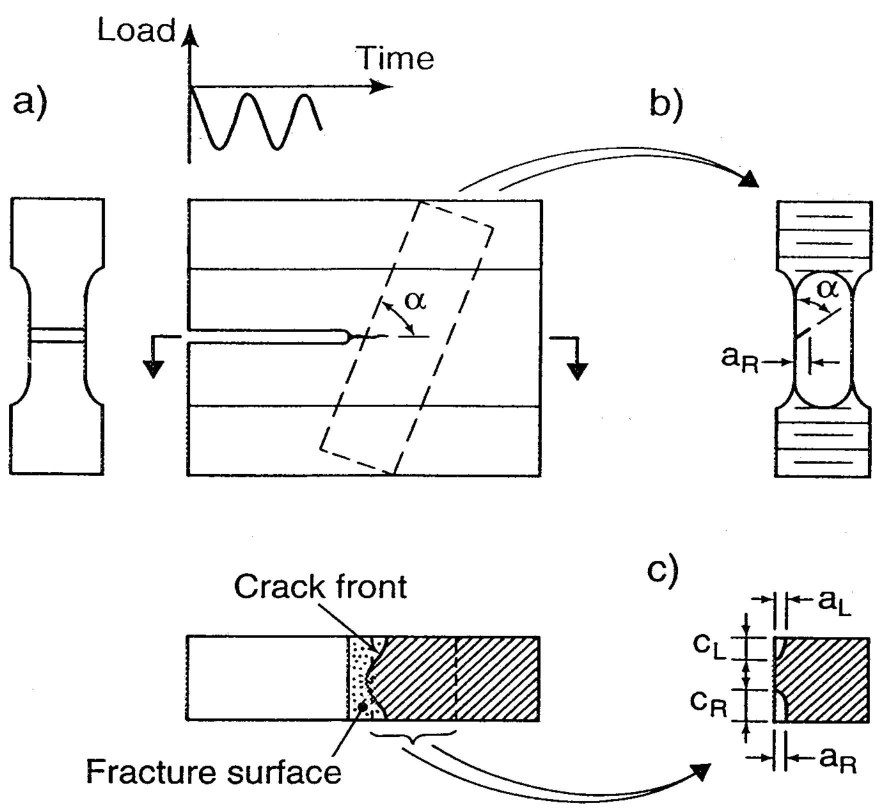

Fig. 1 Schematic of the test-specimen configuration
(a) compact-type (CT) specimen, (b) fatigue tension (FT) specimens, (c) flawed cross-section with nomenclature: a - depth of crack, c - length of crack, L - left side, R - right side

Pre-Cracking and Fatigue Loading

Pre-cracking of the CT specimens was conducted on an AMSLER high-frequency vibrophore testing machine at about ~ 100 Hz sinusoidal compressive loading with a load ratio of $R = (P_{min}/P_{max}) = 10$. At the root of the notch, due to plastic outward flow of the material at P_{min}, the local tensile stresses are induced upon unloading to P_{max}. These tensile stresses are of sufficiently high magnitude to initiate a crack. As the crack advances from the notch-root, the rate of crack growth decreases progressively until a complete crack arrest occurs. Due to the self-arresting nature of the compressive pre-cracking, the extent of damage remaining at the tip of the crack is rather small and does not appreciably affect initial crack growth in the FT specimen. Furthermore, since closure loads during compressible pre-cracking are always negative, this therefore arrives at a naturally closure-free crack at P = 0 condition.

Fatigue tests of flawed FT specimens with small corner cracks (initiated in cyclic compression) are then conducted on an MTS servohydraulic machine at a frequency of 2-3 Hz with a maximum stress of 250 MPa. Load ratios, R, of 0.05 and -0.1 were used for inclined (45°) and perpendicular (90°) corner flaws, respectively.

Crack Monitoring

The technique adopted in this investigation for crack growth monitoring was a replica method. The specimen was first subjected to a load of half of P_{max}, the surface wetted with acetone and the replica placed on the surface. The replica was then taped to a microscope slide for measurement and viewing under an optical microscope. A secant method was used to calculate the growth rate, da/dN, from the crack measurements,

$$\frac{da}{dN} = \frac{\Delta a}{\Delta N} = \frac{a_{i+1} - a_{i-1}}{N_{i+1} - N_{i-1}} \tag{1}$$

as a function of crack depth, a_i.

Determination of Crack Opening Load

The differential compliance method used in Ref. [17] was modified to measure the opening load. The technique utilized was to electronically difference two strain gauge readings (ε_1 - ε_2) : ε_1 (the active gauge) situated over the mouth of the crack on the c-face and ε_2 located such that it was not significantly influenced by the crack, thus measuring the far field. The location of the gauges is shown in Fig. 2a. In Fig. 2a the relative sizes of the gauges and the corner cracks have been exaggerated.

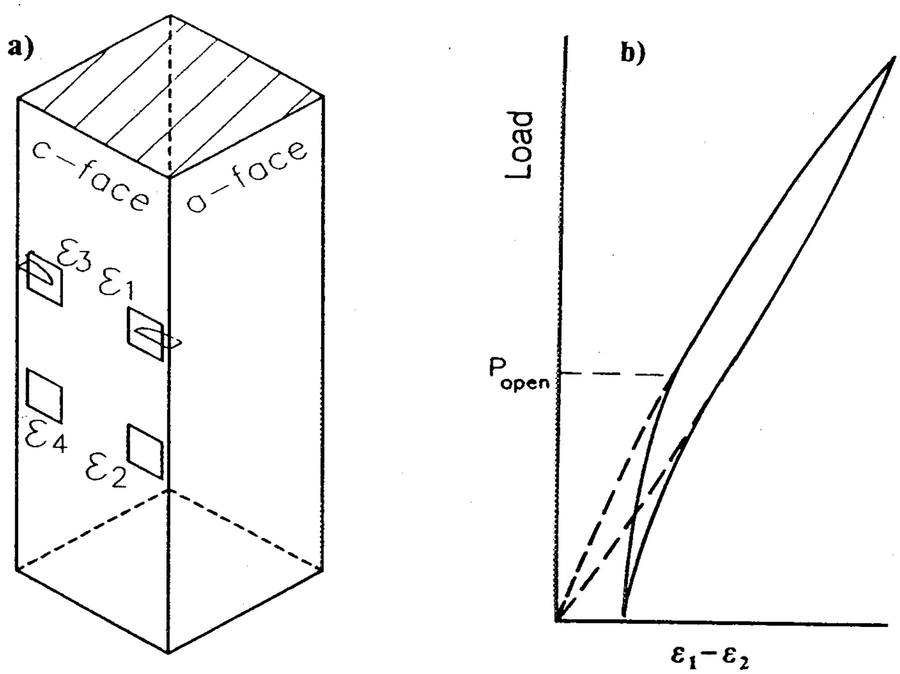

Fig. 2 Schematic illustration of (a) location of strain gauges, (b) differential compliance loop

A dedicated far field gauge, axially in line with the active gauge, was found to improve results from each active gauge compared to using a common far field gauge situated on the back of the specimen. The improved results can be attributed to eliminating the effect of the inevitable bending of the specimen during loading.

The interpretation of the opening load from the differential compliance loop was conducted using a curvilinear fit (illustrated in Fig. 2b) to a power-law (Ramberg-Osgood type) relation

$$\delta = (\varepsilon_1 - \varepsilon_2) = \frac{\Delta P}{M} + \left(\frac{\Delta P}{\bar{M}}\right)^{1/\bar{n}} \tag{2}$$

where δ is the differential displacement, $\Delta P = P_{max} - P_{min}$ is the load range, and M, $\bar{M}$ and $\bar{n}$ are fitted constants. When there is no crack closure, the two loops, i.e. experimental and fitted, will coincide.

The fitted curve is compared to the data to evaluate the opening load by following up the loading branch of the compliance curve to the point where the data curve and the fitted curve come close together. This curvilinear fit was found to be more sensitive than the traditional linear intercept approach, since the present approach takes into account the non-linearity of the applied load-differential displacement loop.

EXPERIMENTAL RESULTS

Typical results of the small corner cracks behaviour, both inclined (45°) and perpendicular to loading direction are presented below.

Inclined Corner Cracks

Figure 3 shows the growth rate, da/dN, versus crack depth, a, for corner cracks initially inclined at 45 degrees. The crack depth measurement was performed using three different microscopes. For each measurement the crack growth rate was computed and the results are plotted with different symbols. The crack extension rate in the through-the-width direction, dc/dN, is also depicted in Fig. 3 as a dashed line.

The da/dN and dc/dN curves generally follow a similar trend except that initially the corner flaws exhibit an erratic growth in the depth direction only. The through-the-thickness crack growth rate, da/dN, becomes continuous when the initially dormant through-the-width crack length, c, starts to propagate. This implies that during the erratic growth stage the orientation of the crack front as well as the crack aspect ratio, a/c, changes. It is interesting to note that the change from the initial crack in Stage I to Stage II crack propagation is rather rapid with a blunt knee transition (see insets in Fig. 3).

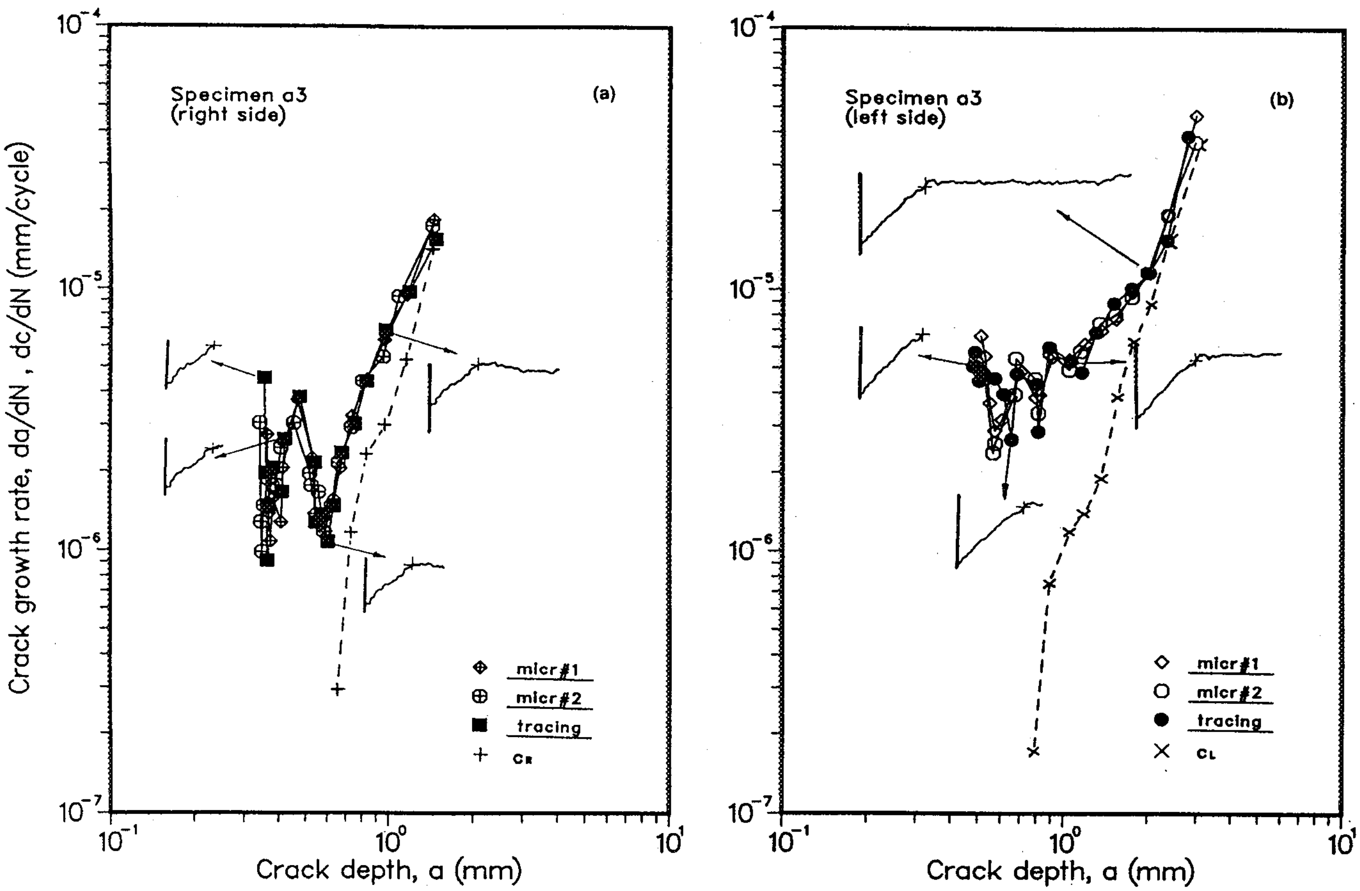

Fig. 3 Crack growth rate vs. crack depth for corner cracks initially inclined at 45°
(a) right side, (b) left side [13]

Figure 4 shows the corner crack aspect ratio, a/c, versus crack depth a. It is seen that the crack aspect ratio is not constant, but increases and the crack tends towards a quarter-circular shape. Similar observations were made in another test [13] with small corner flaws initially inclined at 45° and 60°.

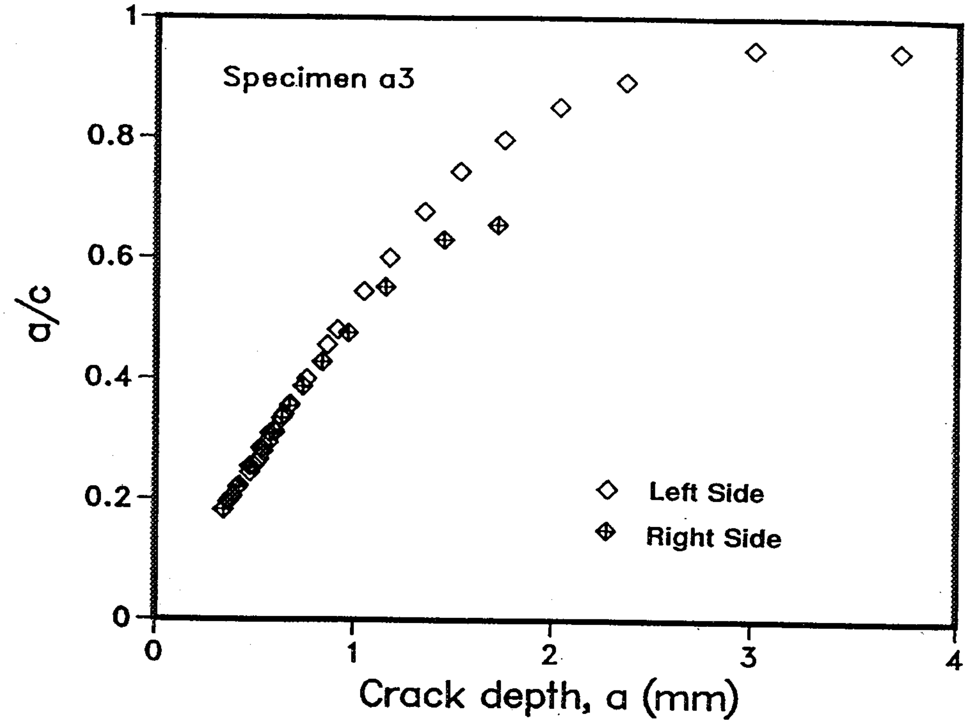

Fig. 4 Crack aspect ratio vs. crack depth for corner cracks initially inclined at 45° [13]

Perpendicular Corner Cracks

Growth rate da/dN and dc/dN versus the depth, a, of the corner cracks (perpendicular to loading direction) is presented in Fig. 5. When the calculated growth rate is less than the scale of the graph, a vertical downward arrow is placed at that data point. A vertical upward arrow is placed at the next point which does show growth and is connected with a dotted line.

Again, the early growth rate, da/dN, is erratic and the corner flaws grow initially in the depth direction only. The continuous crack growth seems to occur after the initially dormant crack length, c, starts to propagate. This is a typical behaviour of small corner cracks. The change in the aspect ratio, a/c, through the test is presented in Fig. 6. The aspect ratio is plotted versus the crack depth normalized with respect to the initial crack size, a/a_o. The value of a_o is included beside the corresponding curve. It is seen that the greater the initial aspect ratio (or larger the initial crack depth), the more quickly the aspect ratio will increase (steeper slope).

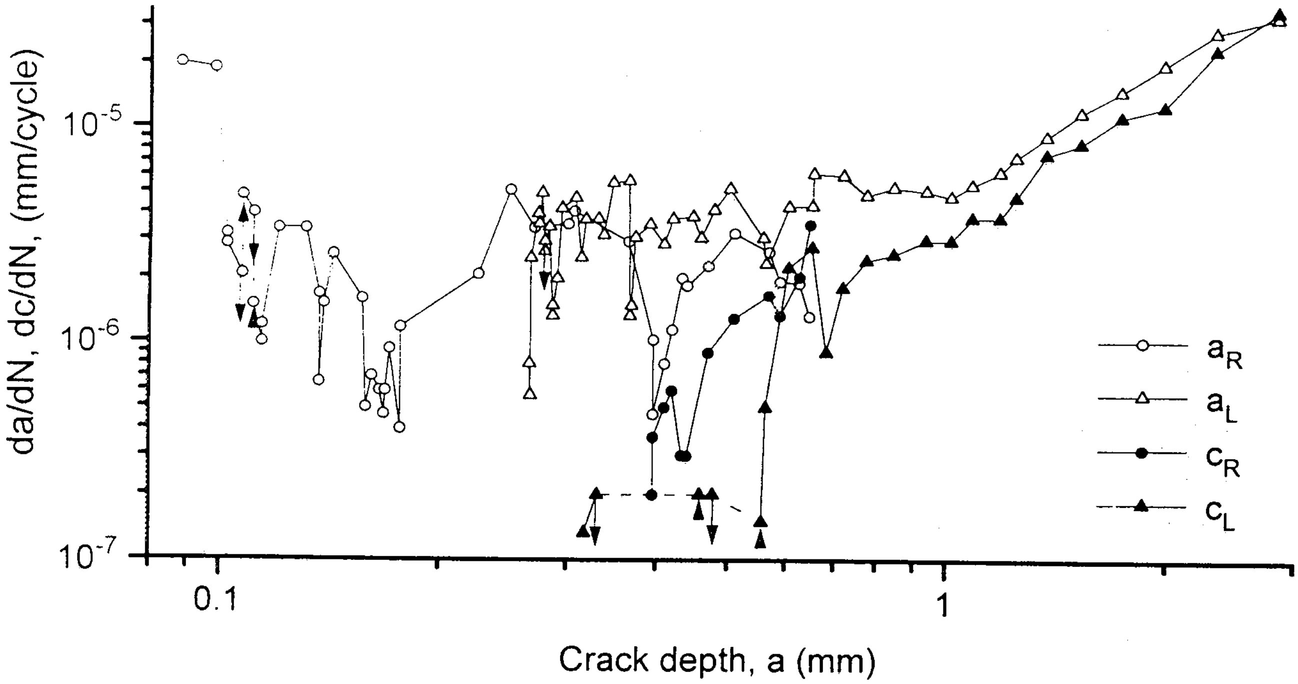

Fig. 5 Crack growth rate vs. crack depth for perpendicular corner cracks

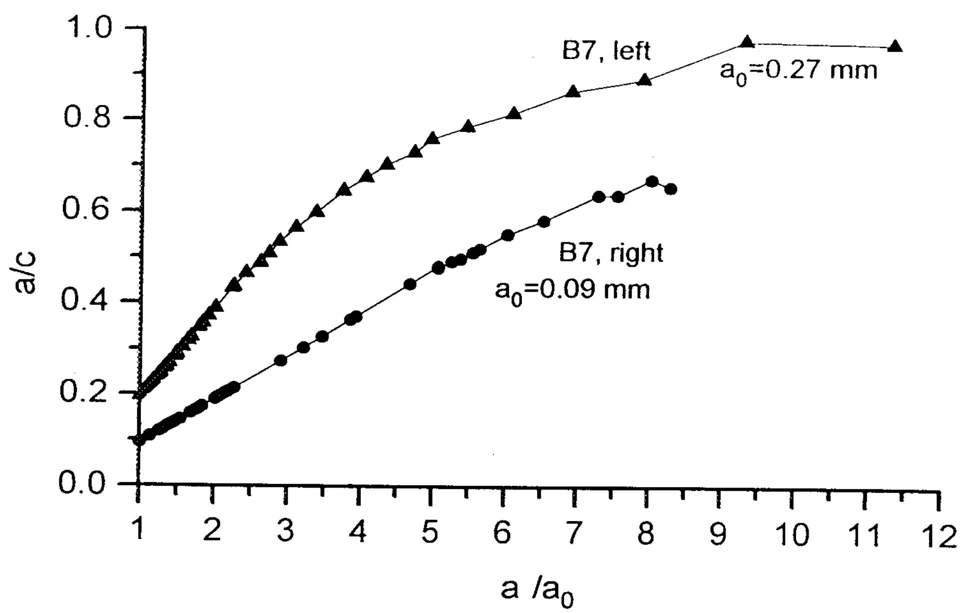

Fig. 6 Crack aspect ratio vs. normalized crack depth for perpendicular corner cracks

The opening load data, P_{open}/P_{max} versus crack extension $\Delta a = a - a_o$, are shown in Fig. 7. The results from each corner crack are presented separately. The opening load decreases initially towards a minimum. This initial drop in crack opening load is probably associated with flattening of the fracture surfaces. As the length of crack wake increases with crack extension in depth, the opening load was found to build up gradually in an irregular manner towards a steady state value.

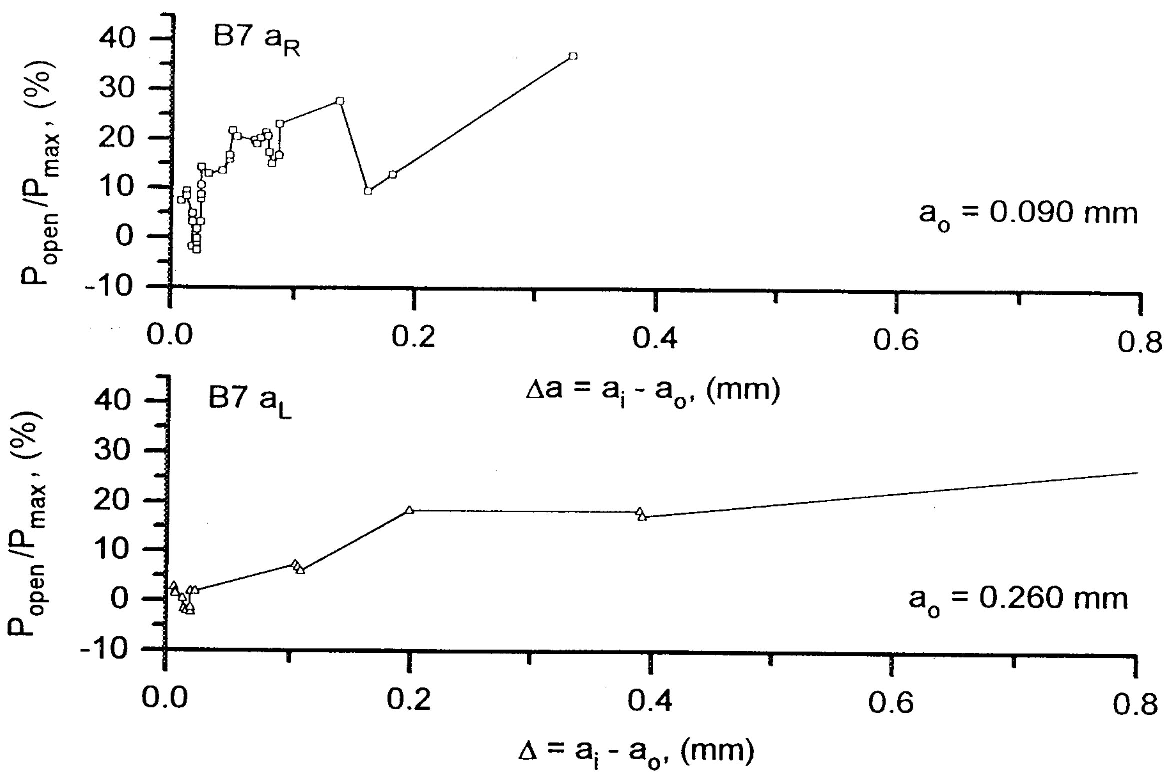

Fig. 7 Relative opening loads vs. crack extension for perpendicular corner cracks

CONCLUSIONS

The techniques presented here provide certain desirable features for the investigation of physically small corner cracks. The specimen preparation method produces a small pre-crack of controllable depth and plane orientation with minimal damage ahead of the tip. During the test this crack/specimen geometry permits one to monitor the development of the crack depth and utilize a strain gauge on the top of the c-face crack for sensitive measurement of the opening load.

These techniques were used to study the small crack behaviour in terms of growth rate and opening load relative to the depth of the crack and its shape.

ACKNOWLEDGEMENTS

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REFERENCES

1. Forsyth, P.J.E.: Fatigue Damage and Crack Growth in Aluminum Alloys. Acta Metall., vol. 11, 1963, pp. 703-715.

2. Taylor, D. and Knott, J.F.: Fatigue Crack Propagation Behaviour of Short Cracks - The Effect of Microstructure. Fatigue Engng. Mater. Struct., vol. 4, 1981, pp. 147-155.

3. Tanaka, K. and Akiniwa, Y.: Modelling of Small Fatigue Crack Growth Interacting with Grain Boundary. Engng. Fract. Mech., vol. 24, 1983, pp. 803-819.

4. Miller, K.J.: Initiation and Growth Rates of Short Fatigue Cracks. In Fundamentals of Deformation and Fracture (Proc. IUTAM Symposium Eshelby Memorial Conference), Cambridge University Press, Cambridge, 1984, pp. 477-500.

5. Lankford, J.: The Influence of Microstructure on the Growth of Small Fatigue Cracks. Fatigue Fract. Engng. Mater. Struct., Vol. 8, 1985, pp. 161-175.

6. Navarro, A. and de los Rios, E.R.: Short and Long Fatigue Crack Growth, A Unified Model. Phil. Mag., Vol. 57, 1988, pp. 15-36.

7. Suresh, S. and Ritchie, O.: Propagation of Short Fatigue Cracks. Int. Metal. Rev., vol. 29, 1984, pp. 445-476.

8. Leis, N.B., Hopper, A.T. and Ahmad, J.: Critical Review of the Fatigue Growth of Short Cracks. Engng. Fract. Mech., vol. 23, 1986, pp. 883-898.

9. McEvily, A.J.: On the Growth of Small/Short Cracks. JSME Int. J., vol. 32, 1989, pp. 181-191.

10. Christman, T. and Suresh, S.: Crack Initiation under Far-Field Cyclic Compression and the Study of Short Fatigue Cracks. Engng. Fract. Mech., vol. 23, 1986, pp. 953-964.

11. Lam, Y.C., Kujawski, D. and Ellyin, F.: The Development of the Crack Closure with Crack Extension. Scripta Metallurgica and Materialia, vol. 25, 1991, pp. 2313-2318.

12. Kujawski, D. and Ellyin, F.: Propagation of Small Corner Cracks Initiated in Cyclic Compression. Engng. Fracture Mech., vol. 43, no. 4, 1991, pp. 657-662.

13. Kujawski, D. and Ellyin, F.: Fatigue Growth of Physically Small Inclined Cracks. Fatigue Fract. Engng. Mater. Struct., vol. 16, no. 7, 1993, pp. 743-752.

14. Craig, D.: The Growth and Behaviour of Short Cracks in a Ferrit/Pearlitic Steel. M.Sc. Thesis, Department of Mechanical Engineering, University of Alberta, 1994.

15. Ellyin, F., Kujawski, D.: Plastic Strain Energy in Fatigue Failures. ASME J. Pressure Vessel Tech., vol. 106, 1984, pp. 342-347.

16. Pippan, R.: The Length and the Shape of Cracks under Cyclic Compression: The Influence of Notch Geometry. Engng. Fract. Mech., vol. 31, 1988, pp. 715-718.

17. DuQuesnay, D.L.: Fatigue Damage Accumulation in Metals Subjected to High Mean Stress and Overload Cycles. Ph.D. Thesis, University of Waterloo, 1991.